

ON THE TEMPERATURE-EFFECT OF THE DAILY VARIATION OF COSMIC RAY MESON INTENSITY

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(Received June 11, 1962)

ABSTRACT. The effect of the daily variation of atmospheric temperature on the daily variation of cosmic ray meson intensity recorded at ground level is discussed. Estimates of possible magnitudes of temperature effect are critically examined and shown to be rather unsatisfactory. Using for the temperature coefficient an *ad hoc* value of $0.02\%/^{\circ}\text{C}$ of ground temperature, past results regarding long-term changes of the amplitudes and hours of maxima of the first and second harmonic of daily variation of cosmic ray meson intensity are re-examined. It is shown that the temperature correction causes appreciable changes. However, in view of the divergent estimates of the temperature effects obtained so far, it is emphasised that a rigorous attempt at accurate experimental determination of daily variation of upper atmospheric temperatures is urgently needed.

INTRODUCTION

The atmospheric effects of cosmic ray intensity may be classified as :-

- (a) Barometric pressure effect.
- (b) Effect of liquid water content of over-hanging clouds.
- (c) Effect of passage of cold and warm air fronts.
- (d) Effect of snow deposition above the instrument.
- (e) Effects due to temperature distribution in the atmosphere.

Amongst these, the pure absorption effects (a) and (d) are well understood. For neutron intensity, the barometric pressure coefficient is about $0.96\%/ \text{mm.Hg}$. (It is not quite known whether it is the same for high and low altitudes). For mesons, it is $0.22\%/ \text{mm.Hg}$ for high latitude sea-level stations. As shown by Wada (1960), it reduces to $0.19\%/ \text{mm.Hg}$ for equatorial, sea-level mesons. Also, both these coefficients increase rapidly with altitude, e.g., the value for mesons at Huancayo (alt. 3.4km) at equator is about $0.33\%/ \text{mm.Hg}$. If the barometric pressure records at ground level are available, the barometric pressure effect can be adequately corrected for. Absorption due to deposition of snow above the instrument can also be corrected for if the snow thickness can be measured. Usually, workers prefer to eliminate this effect by continuously melting the snow by artificially heating the roof.

The effect of liquid water content of over-hanging clouds is a very uncertain factor (Arakawa, 1959). Since it does not affect the barometric pressure recorded

at ground, it is not taken care of by barometric correction. The effect is negligible for mesons but can be quite large $\sim (1-2\%)$ for neutrons. There is no simple way of correcting for it.

Effect of the passage of warm and cold air fronts seems to be more prominent for mesons than for neutrons. In principle, it can be corrected for if the temperature distribution of the atmosphere is known. However, in the dynamic, rapidly changing conditions of the atmosphere during storms, it is difficult to determine the temperature distribution. Hence, a correction becomes difficult.

The temperature distribution in the atmosphere directly affects the heights of the meson formation layers. Due to the limited life-times of mesons, their decay probabilities and hence their intensities at ground level are affected. For neutron intensity, the temperature distribution plays negligible role. For mesons, the variations at ground are adequately represented by the equation (Dorman, 1957)

$$\frac{\delta N_\mu}{N_\mu} = \beta \cdot \delta h_0 \cdot \int_0^{h_0} W(h) \cdot \delta T(h) \cdot dh \quad (1)$$

where $\delta N_\mu/N_\mu$ is the fractional change of μ meson intensity at the atmospheric depth h_0 , β is the barometric coefficient, δh_0 is the actual change in barometric pressure at depth h_0 , $W(h)$ is the temperature-coefficient density and $\delta T(h)$, the actual temperature change at an atmospheric depth, h . As already mentioned, β is precisely known. The values of $W(h)$ for various atmospheric depths are also precisely known from theoretical calculations by Dorman. Therefore, to evaluate (1), one needs records of ground level pressure changes (δh_0) as also of the atmospheric temperature distribution $\delta T(h)$. In practice, the integral may be broken up into summation over a series of isobaric levels (say, 100 mb apart) for each of which the average temperature change δT may be available from Radiosonde data.

Now, Radio-sonde data are usually available for any station from only one or two flights a day. For correcting the *daily mean intensity* of μ mesons, one can use the averages of these flights for every isobaric level. However, if the correction $\delta N_\mu/N_\mu$ is needed for daily variation of cosmic rays, one either needs values of $\delta T(h)$ also at small time intervals, or, one has to know precise relations (theoretical or empirical) between variations of ground level temperature and simultaneous variations of temperatures at various atmosphere depths. Unfortunately, the altitude dependence of the daily variation of atmospheric temperature is not precisely known. Various workers have given various estimates. Some of these are experimental determinations, most of which are often considered of doubtful accuracy because of what are known as "Radiation errors" (Brasefield, 1948). There are several theoretical estimates too. Table I gives a summary of presently available information.

TABLE I

Investigator	Place	Season	Amplitude of daily variation at														
			Km. 0	0.3	0.5	1.0	1.5	2.0	3.0	4.0	10.0	15.0	20.0	30.0			
			Mb. 1000	975	955	900	845	800	700	610	280	120	55	10			
Van Bemmelen (1916)	Batavia,		5	0.7	0.4	0.7	0.4										
Barkov (1917)	Lindenbergl		3	1.9	1.2	0.9	0.4										
Dries (1919)	Drexel, U.S.A.		5		1.1	0.8	0.6										
Schmidt (1925)	Eiffel Tower, Paris		5	2.2													
Geiger <i>et al.</i> (1932)	Gross Arbor, Bavaria					2.0°C	1.1°C	0.8°C									
Wolf <i>et al.</i> (1946)	U.S.A.	Summer															
		Winter															
Piegsa (1947)	Liverpool, U.K.																
Scherlag (1948)	Germany																
Kay (1951)	British Isles																
Brunt (1952)	Lunderberg	Summer	5														
		Winter	5														
Venkatesvaran and Desai (1953)	Ahmedabad, India																
Belmont (1954)	Greenland																
Scrase (1956)	U.K.																
Kanmer (1956)	U.S.S.R.		5		2.0			0.8	0.5	0.8	1.4	2.0					
Harris (1959)	U.S.A.		5		1.8			0.7	0.3	0.3	0.3	0.3					
Chiu (1959)	U.S.A.	Summer															
		Winter															
Pant (1960)	India																
Jordan (1960)	Tropical Pacific																
Rangarajan and Sikka (1962)	India																
Haurwitz (1936)	Theoretical																
Elasser (1940)	"																
Beers (1944)	"																
Penner (1948)	"																
Wexler (1950)	"																
London (1951)	"																
Johnson (1953)	"																
Pressman (1955)	"																

As can be seen from Table I, evidence regarding ranges of daily temperature at different altitudes is very uncertain indeed. While some workers claim no significant ranges, some others claim ranges as high as 5°C even at 15 km. altitudes. Now in equation (1), if the integral is replaced by a summation, the temperature effect could be represented by

$$\frac{\delta N_{\mu}}{N_{\mu}} = \sum K_i \cdot \delta T_i, \quad \dots (2)$$

where K_i is the partial temperature-coefficient and T_i is the average temperature variation of the i -th layer. For K , Dorman's calculated values are as shown in Table II.

TABLE II

$H(mb)$	1000	900	800	700	600	500	400	300	200	100
$K_i(\%/^{\circ}\text{C})$ (negative)	.020	.021	.022	.024	.025	.026	.028	.033	.038	.031

If, as an extreme assumption, the diurnal variation of ground temperature is depicted to the same extent by all layers high up in air, the integrated effect would be about 0.27% per degree change at ground, which for a sea-level station like Ahmedabad, India, where ground temperature amplitudes can be as high as $\pm 10^{\circ}\text{C}$, would imply a diurnal contribution of about 2.7% oppositely correlated to ground temperature. On the other hand, if the diurnal variation of temperature reduces rapidly with altitude and is negligible after 2 km. altitude, the total contribution would reduce to about 0.3% or less. Considering the fact that the average amplitudes for meson telescopes for groups of days are only of the order of 0.5% or less, the uncertainty due to temperature correction is a very disconcerting feature indeed.

In view of the lack of proper information about diurnal variation of upper atmosphere temperatures, workers have attempted to estimate *indirectly* the contribution of temperature effect to the diurnal variation of cosmic ray mesons. In the next section, such attempts by other workers as also some analysis by the present author will be discussed.

EXPERIMENTAL STUDIES

From comparison of the average diurnal variation curves for different seasons, Dorman (1957) has concluded that the total contribution of temperature effect to diurnal variation of cosmic ray mesons is of the order of 0.10 to 0.30% depending upon the season. From the approximately linear motions of the tips of the vectors representing the first harmonic on a harmonic dial for 1953-54-55, Glukova (1960) has concluded that the daily variation of meson intensity is the resultant of a variable vector of external origin and a constant vector of most probably atmos-

pheric origin. From the data of several Ionisation chambers and meson telescopes, the constant vector seems to be of amplitude between about 0.05 and 0.12% and an hour of maximum in the early morning. This could be interpreted as the expected temperature effect. Unfortunately, the amplitudes differ largely from place to place. Also, the method gives only approximate estimates of the constant vector. The estimates could be wrong if the external vector had changed in both amplitude and phase from month to month.

Quenby and Thambyahpillai (1960) have estimated the temperature effect from a comparison of neutron monitor and Ionisation chamber data for Huancayo. Their basic idea is this. The neutron intensity is affected by atmospheric pressure but not by atmospheric temperature distribution. Also, for an equatorial station like Huancayo, the coupling constants for neutron and meson intensity are somewhat similar. (Webber and Quenby, 1959) In addition, a neutron pile and an ionisation chamber have roughly similar zenith angle responses. Hence, effects shown by the neutron pile and the ionisation chamber at equator (after proper barometric correction is applied to both) will be similar except for a possible temperature effect in the meson intensity (ionisation chamber). If periods are chosen when the daily variation for the neutron pile is negligibly small, the ionisation chamber will have no daily variation of extra-terrestrial origin. Hence an observed daily variation, if any, can be attributed to atmospheric temperature variations only.

Using this elegant idea, Quenby and Thambyahpillai (1960) selected months when the monthly average diurnal variations for Huancayo neutron pile were negligibly small ($<0.1\%$). They found that the average diurnal variation for the ionisation chamber for the same periods showed amplitudes of about 0.11% with the hour of maximum at 05.30 hrs (L.T) which is in very good negative correlation with the diurnal ground temperature wave at Huancayo. The period studied was 1953-55.

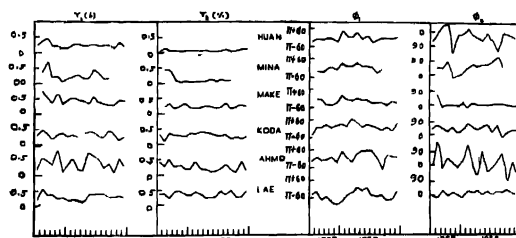


Fig. 1—Monthly average amplitudes (r_1 , r_2) and hours of maxima (ϕ_1 , ϕ_2) of first and second harmonics of daily variation of neutron intensity at the equatorial station of Huancayo, Mina Aguilar, Makerere, Kodaikanal, Ahmedabad and Lae.

During the I.G.Y., several neutron monitors, meson telescopes and ionisation chambers were operating simultaneously all over the world. An attempt was made to use these to estimate the contribution of temperature effect. The equatorial stations where neutron and meson data were recorded simultaneously were Kodaikanal, Ahmedabad, Lac, Makerere and Huancayo. Now, following Quenby and Thambyahpillai's method, one should first separate out the months for which the average monthly amplitudes for neutrons are negligibly small. It was found, however, that the average daily variation amplitudes were rather high (0.2% or more) throughout the I.G.Y. period. The values of the monthly average amplitudes (r_1 and r_2) and hours of maxima (ϕ_1 and ϕ_2) of the first and second harmonics for several equatorial neutron monitors are plotted in Fig. 1. It may be noted that :

- (a) For most of the months, r_1 is $> 0.2\%$, in some cases as high as 0.6% . The value of r_2 is comparatively small.
- (b) Values of r_1 are not similar at all stations. Some stations (e.g. Ahmedabad) show much larger fluctuations of r_1 as compared to other stations. The pressure coefficient used for all these data is the same, about $0.72\%/mb.Hg$. Statistical errors are negligibly small. Dissimilarity between the number of days in the same month for different stations could be a possible cause. Also improper working of the instruments is not ruled out. The erratic fluctuations of the hour of maximum indicate possibly the same cause.

For these reasons, it became difficult to select months of negligibly low amplitudes. Nevertheless, the following grouping was adopted :

Group A—(Low amplitudes) Jul., Dec. 1957; Jan. Mar. Apr. Aug. Oct. Dec., 1958.

Group B—(Medium), Oct. 1957, Feb., Jul., Sep., Nov., 1958.

Group C—(High), Aug., Sep., Nov. 1957; May, June, 1958.

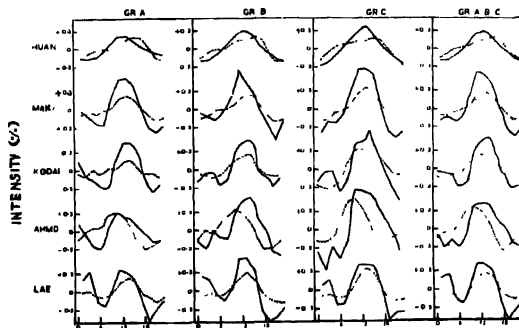


Fig. 2—Average diurnal variation curves for neutrons (full lines) and mesons (dotted lines) for Huancayo, Makerere, Kodaikanal, Ahmedabad and Lac for months of Low (Gr. A), Medium (Gr. B) and High (Gr. C) amplitudes r_1 .

Fig. 2 shows the average diurnal variation curves for neutrons and mesons (Ionisation chamber for Huancayo and cubical mesons for the others) for the three groups for various stations. In general, the mesons do show lesser amplitudes than neutrons and the difference indicates a negative correlation with an average ground temperature curve for the meson intensity. However, the differences are different from place to place. If all these are considered as fault-free and if it is assumed that the neutron and meson curves would have looked alike if the mesons were corrected for temperature effect, the temperature effect would amount to anything from 0.0 to 0.5%. Thus is rather a large contribution.

Amongst the various data referred to above, those for Huancayo neutrons and mesons appeared to be the most reliable. Hence, a separate analysis was made for Huancayo, dividing the 1 G.Y. period into 4 groups as follows :

Group 1—(Very low amplitudes) Jul , Dec., 1957; Jan. Oct., 1958.

Group 2—(Low amplitudes) Oct. Nov , 1957, Apr., May, Jul., Sep , Dec., 1958

Group 3—(Medium amplitudes) Feb., Mar., Jun, Aug., 1958.

Group 4—(High amplitudes) Aug., Sep., 1957; Nov., 1958.

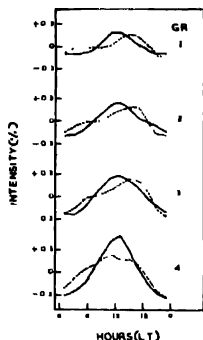


Fig. 3—Average diurnal variation at Huancayo for neutrons (full lines) and mesons (dotted lines) for months of Very Low (Gr 1), Low (Gr. 2), Medium (Gr 3) and High (Gr. 4) amplitudes r_1 .

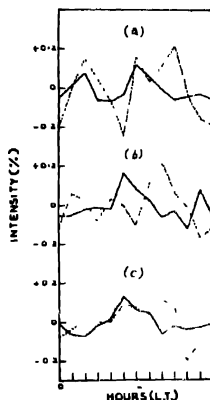


Fig. 4—Average diurnal variation at Huancayo for neutrons (full lines) and mesons (dotted lines) for days on which r_1 values were in the ranges (a) 0.00--0.10%, (b) 0.11--0.15%, (c) 0.16--0.00%.

Fig. 3 shows the average daily variation curves for those 4 groups for Huancayo neutron (full lines) and Ionisation Chamber (dotted lines). Here again, if it is assumed that neutrons and mesons should show similar variations but for the temperature effect on mesons, the temperature effect amounts to as large as 0.3% for Group 4. On the other hand, in Groups 1, 2, 3, the amplitudes of neu-

trons and mesons are almost alike but the hours of maxima are earlier for neutrons. It seems, therefore, that the assumption regarding similarity of daily variations for mesons and neutrons is not fully justified and the temperature effect estimated by the above method would be only approximate.

As it was not possible to pick out months showing average diurnal variation amplitudes less than $\sim 0.15\%$ for neutrons, an attempt was made to examine *individual days* and choose those of negligible amplitudes. For this, the neutron intensity at Huancayo was used and the bi-hourly deviations from mean for every day for which data were available during I.G.Y. were harmonically analysed, after applying linear correction for long term changes by calculating running averages over 12 successive bi-hourly values as usual. Days were then sorted out according to values of the amplitude r_1 of the first harmonic lying in the following ranges :

Range (a)	$0.00 \leq r_1 \leq 0.10\%$
„ (b)	$0.11 \leq r_1 \leq 0.15\%$
„ (c)	$0.16 \leq r_1 \leq 0.20\%$

For days in each range, the average daily variation for neutrons and mesons was computed. The results are shown in Fig. 4. A very interesting point to note is that whereas days are chosen so as to have negligible amplitudes r_1 , the final curves do not show negligible deviations. This is because the amplitude r_2 of the second harmonic is not simultaneously negligible. Most of the curves in Fig. 4 are with two maxima during 24 hours, indicating an appreciable contribution of second harmonic. If an additional condition is imposed viz. that r_2 also should be in the same range as r_1 , the number of days in each group becomes very small, and the method cannot be pursued further. Table III gives the amplitudes and hours of maxima of the first and second harmonic for curves in Fig. 4.

It will be seen from Table III that the Neutron minus Meson curve which is expected to show an hour of maximum coinciding with that of ground temperature curve, does not show the effect either for the first or for the second harmonic. In fact, the phases of the two are in opposition which would imply a "Positive Temperature effect"!

It would be seen from the above discussion that the method suggested by Quenby and Thambyahpillai fails when applied to the I.G.Y. data. A possible reason could be that whereas in the period 1953-55 studied by them, the solar activity was low and the spectrum of the anisotropy causing daily variation was flat enough to give similar results for neutrons and mesons at equator, the increased solar activity during the I.G.Y. might have created complications.

Because of the failure of this method, a different approach was attempted. It is well-known that the daily variation of cosmic rays changes from month to month. The changes could be due to seasonal variations of ground temperature

TABLE III

Component	Group (a)			Group (b)			Group (c)		
	r_1 (%)	ϕ_1	r_2 (%)	ϕ_2	r_1 (%)	ϕ_1	r_2 (%)	ϕ_2	r_1 (%)
Neutrons	0.026	$\pi - 9^\circ$	0.054	$\pm 32^\circ$	0.056	$\pi - 25^\circ$	0.057	$\pi - 12^\circ$	0.045
Mesons	0.062	$\pi \pm 40^\circ$	0.150	$\pi - 52^\circ$	0.062	$\pi - 33^\circ$	0.097	$\pi - 57^\circ$	0.047
Neutrons minus mesons	0.049	$\pm 63^\circ$	0.146	-31°	0.058	-89°	0.151	-47°	0.086
ground temperature	5.9°C	$\pi - 28^\circ$	1.3°C	-9°	5.9°C	$\pi \pm 38^\circ$	1.3°C	$\pm 9^\circ$	1.3°C

or due to sidereal effects or due to long-term changes of the solar component which may be misinterpreted as seasonal effects. In practice, it is almost impossible to separate the three, specially from a limited amount of data. However, during the last 25 years, Forbush and his coworkers (1948, 1957; 1961) have done an admirable job of obtaining more or less continuous and reliable data from Ionisation chambers at Huancayo, Cheltenham (recently shifted to Fredericksburg) and Christchurch. One can, therefore, adopt the following argument :

From data for a few years, the seasonal variation cannot be properly studied because the solar vector also changes from month to month. However, if continuous data for, say, 2 solar cycles (22 successive years) are available, the long-term linear trends in daily variation would be greatly minimised. The following procedure could now be adopted :

- (i) Evaluate the monthly average daily variation curves (bi-hourly % deviations) for any station for $22 \times 12 = 264$ consecutive months.
- (ii) Average data for similar months, thus yielding 12 daily variation curves for January to December.
- (iii) Find the yearly average curve by combining the 12 monthly curves and subtract this from the curve for each month yielding thus a set of 12 bi-hourly percentage deviations from mean for each month.
- (iv) From data of ground temperature for any 3-4 successive years, evaluate a set similar to (iii) above.

Since monthly average ground temperature daily variation does not change much from year to year, an average for any 3-4 consecutive years would be a good representative for any period. Because we have subtracted the yearly average

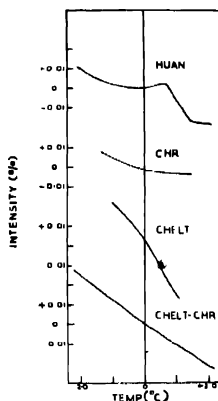


Fig. 5—Cosmic ray meson intensity vs ground temperature (from daily variation curves).

from the monthly curves for temperature also, the sets of 12 bi-hourly values of cosmic rays and ground temperature for every month can be directly compared. If a sidereal variation does not exist, one would expect a perfect negative correlation between the two.

The above procedure was adopted for the Ionisation Chamber data at Huancayo for the period 1937-59. It was noticed that the correlation coefficients did not exceed 0.5 for any month. Also, the coefficients were sometimes positive. It was obvious, therefore, that temperature variations were not the only cause of the month-to-month changes of daily variation. A possible sidereal variation could be the disturbing factor. Also, long-term changes in the solar factor may not have been completely eliminated. There was no straight-forward method of estimating these or applying corrections for the same. A statistical approach could be to give weightage to temperature deviations only. Thus, the 12 sets of 12 bi-hourly values of cosmic rays were grouped in such a way that the corresponding temperature deviations lay in fixed ranges. Fig. 5 shows the plot of average cosmic ray values *vs* temperature ranges. In general, lower temperatures are associated with higher cosmic ray intensities and vice versa. But an actual correlation analysis yields a regression coefficient of only $-0.007\%/^{\circ}\text{C}$. At Huancayo, the yearly average amplitude of ground temperature is about $\pm 7^{\circ}\text{C}$. Hence the contribution to cosmic ray meson intensity would be only 0.05% in contrast to 0.11% reported by Quenby and Thanbyahpillai.

Using data for about 20 years for Ionisation chambers at Cheltenham and Christchurch, a similar analysis was carried out. These results are also shown in Fig. 5. The coefficient for Christchurch is very low, about $-0.004\%/^{\circ}\text{C}$, but for Cheltenham, it is quite high, about $-0.029\%/^{\circ}\text{C}$ (temperature data for Washington D. C. were used). Now, if there is a sidereal effect affecting all these data, it is expected to be the same for Cheltenham and Christchurch and hence should cancel out in their difference. On the other hand, since these two stations are in different hemispheres, temperature differences will persist. Hence, a similar analysis was carried out for Cheltenham minus Christchurch, adopting a similar procedure for ground temperatures also. The plot is shown in Fig. 5. The regression coefficient is $-0.011\%/^{\circ}\text{C}$.

For the period 1936-40, Hogg (1949) has published Ionisation chamber data for Canberra. When a similar analysis was carried out for these data, it yielded a positive correlation between cosmic ray intensity and ground temperature! Data for Ionisation Chamber at Itabashi (Japan) for the period 1953-60 were also analysed. A negligible correlation between cosmic rays mesons and ground temperature was obtained.

Table IV summarises the various estimates of temperature effect referred to so far.

IMPLICATIONS OF TEMPERATURE CORRECTION

From the evidence presented so far it seems that the situation regarding the estimation of temperature effect on the daily variation of cosmic ray mesons is very unsatisfactory indeed. Not only is the magnitude of the effect not precisely known but even the upper limit of the effect expected is difficult to determine. From some results, it would seem as if the effect is probably less than about 0.15% for yearly average curves. On the other hand, some data on upper air temperatures would put an upper limit as high as 0.5%. In studies with narrow

TABLE IV

Source of information	Total temperature effect on cosmic rays (%)	Temperature coefficient (%°C of ground temperature)
From experimentally determined daily variation of upper air temperature	0 to 2.0	0 to 0.3
Beer's relation (Table I)	0.20	0.03
Quenby and Thambyahpillai,		
High altitude	0.11	—
Sea-level	0.16	—
Dorman's estimate	0.10 to 0.30	—
Present analysis :—		
Comparison of <i>N</i> and <i>M</i> curves,	0 to 0.5	
Seasonal variation analysis,		
Huancaayo	0.05	0.007
Christchurch	0.03	0.004
Cheltenham	0.20	0.029
(Chilt-Christ)	0.08	0.011
Canberra	Positive effect	
Itabashi	Negligible	
Glokova, from long-term changes of daily variation during solar minimum	0.05 to 0.12	

angle telescopes, one usually finds daily amplitudes as high as 1.0%. It is, therefore, argued that the pollution due to temperature effect on such days would be small. It must be remembered, however, that on individual days, the daily range of ground temperature, specially at sea-level inland stations, can be quite large. Table V gives the maximum, minimum and average monthly range for 1959 for Ahmedabad, India (sea-level, geographic lat. 23°. ON, long. 72° 5E).

TABLE V

Month	Ground temperature range ($^{\circ}\text{C}$)		
	Maximum	Minimum	Monthly average
January	20.0	9.1	15.3
February	20.1	10.6	16.2
March	20.5	10.5	16.6
April	20.2	9.3	14.5
May	17.0	10.6	13.9
June	15.6	5.6	10.3
July	8.5	0.9	4.8
August	6.2	0.9	4.3
September	10.1	2.0	5.4
October	16.1	3.7	9.5
November	16.7	4.7	13.8
December	18.7	6.5	15.3

Thus, in the winter months, one encounters days of temperature range as high as 20°C , which will give an amplitude of about $\pm 10^{\circ}\text{C}$, while in monsoon months, the range may drop down to 0.9°C yielding an amplitude of $\pm 0.5^{\circ}\text{C}$ only. As shown in Table IV, the temperature coefficients may be anything from 0 to $0.2\%/^{\circ}\text{C}$ and thus daily temperature effects may amount to as much as 1.0% or more. The precise contribution depends upon the precise value of the coefficient which itself may be different for different locations and for different seasons. Thus, there is no reason to be complacent about temperature corrections at any period.

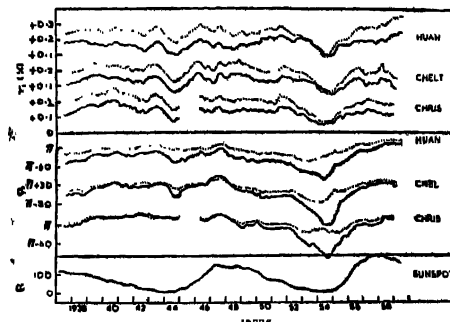


Fig. 6—Long-term changes of the amplitude r_1 and hour of maximum ϕ_1 of the first harmonic before (full lines) and after (dotted lines) temperature correction.

It would be interesting to examine at this stage the implications of a temperature correction to daily variation of meson intensity in the light of the various results that have been published in the past. Sarabhai and Kane (1953), Thambyahpillai and Elliot (1953) and Sarabhai *et al.* (1954) have shown that the yearly average amplitude and phase of daily variation of cosmic ray meson intensity show fluctuations in relation to the 11 year and 22 year solar cycle. Fig. 6 is a plot of the amplitudes r_1 and hours of maximum ϕ_1 of the first harmonic, each point being obtained as running average of 12 consecutive monthly values. Full lines represent data corrected for barometric pressure only and are similar to those illustrated in the publications referred to above, except for the period 1946-58 for Huancayo. For this station the pressure records were read wrongly in this period (Forbush and Beach, 1961) and hence the data published earlier were wrongly pressure-corrected. The necessary changes in the vectors a_1 and b_1 and hence in r_1 and ϕ_1 are given by Forbush and Beach and have been used in the present analysis for obtaining the curves for Huancayo in Fig. 6. The dotted lines in Fig. 6 represent the amplitudes and hours of maximum after correcting for temperature effect by using a coefficient of 0.02% per °C of ground temperature. For Huancayo, it amounts to adding a vector of amplitude of about 0.12% parallel to ground temperature vector and is roughly the same as Quenby and Thambyahpillai's estimate of temperature effect.

As can be seen from Fig. 6 the correction for temperature effect does the following

- a) The amplitude r_1 is now in general larger than before and remains essentially constant except near the solar minimum years of 1944 and 1954 when the amplitudes go down. The depression in 1954 is conspicuously larger and is spread over longer period (1952-55) in contrast to that in 1944 (1944-45 only). It possibly indicates a minor 11 year cycle included in a major 22 year cycle. The forthcoming solar minimum will soon give a part confirmation of this pattern.
- b) The hour of maximum ϕ_1 without temperature correction shows a shift towards earlier hours during solar minimum, which is more marked for 1954 (about 8 hours) than in 1944 (about 3 hours) indicating an 11 year cycle within a 22 year cycle. It is interesting to note that, after temperature correction, the variations in hour of maximum are reduced considerably. In 1944 the shift is not even discernable. In 1954, it amounts to only about 3 hours. The 22 year cycle becomes more obvious and the minor 11 year cycle disappears. Here again, confirmation over one more 22 year cycle is necessary.

The actual amount of shift in the hour of maximum is directly related to changes in the energy spectrum of the anisotropy of daily variation and its direction in space. Assuming that the energy spectrum remains constant and the

average geomagnetic deflection for cosmic rays arriving at Huancayo is about 90° , the normal hour of maximum at about 12 noon for Huancayo indicates an anisotropy in the 18 hr. direction. In 1944 it shifts by 3 hours and in 1954 by 8-9 hours thus crossing the earth-sun line by 1954. If, however, a temperature correction is applied, the direction changes utmost by 3 hours and hence is always on the same side of the earth-sun line. This would have an important bearing on the theories of daily variation.

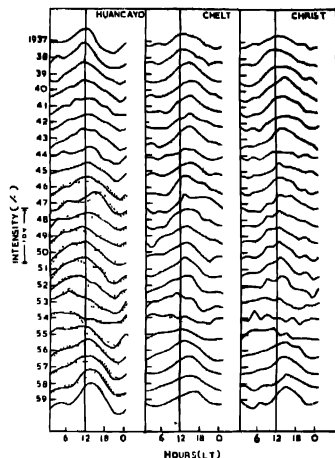


Fig. 7—Daily variation curves for Huancayo, Cheltenham and Christchurch for 23 years. For Huancayo, the dotted curves for 1946-58 are the wrongly pressure-corrected ones.

The shifting of the hour of maxima by as much as 8 hours had indicated another possibility. Sarabhai *et al.* (1955) have shown that from 1937 to 1954, the daily variation curves had undergone a drastic change from curves of day-time maximum to night-time maximum. Unfortunately, the conclusion was based mainly on the Carnegie Institution data for Huancayo for which the data for 1946-58 are wrongly pressure-corrected as stated earlier. Fig. 7 shows the average daily variation curves for 23 years (1937-59) for Ionisation chambers at Huancayo, Cheltenham and Christchurch. For Huancayo, the dotted lines represent the earlier data which were wrongly pressure-corrected. The full lines are for properly pressure-corrected data. As can be seen for Huancayo, the hour of maximum is at about local noon from 1937 to 1945. From 1946 onwards, it looks as if a second peak is developing at or before 06 hours. The effect is more prominent in the dotted curves (wrongly pressure-corrected) but is seen in the full curves also. By 1954, the original day-time peak has disappeared leaving only one peak during night-time, again more prominent in dotted curves. For Cheltenham and Christ-

church, the effect is not so clear but in 1954 there does appear a possibility of night-time maximum.

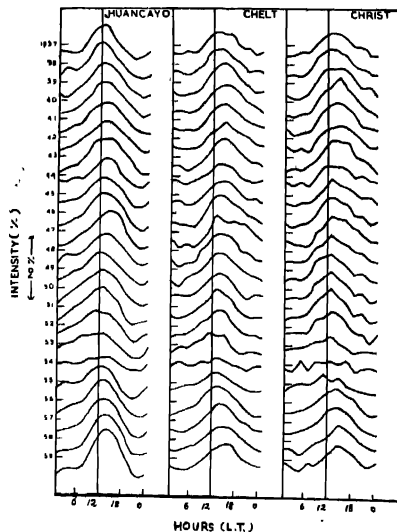


Fig. 8—Daily variation curves for Huancaayo, Cheltenham and Christchurch after temperature correction.

Fig. 8 shows the yearly average daily variation curves after correction for temperature effect ($0.02\%/^{\circ}\text{C}$). A marked change from Fig. 7 is obvious. The hour of maximum is throughout in the noon or afternoon and all that happens in 1954 is a drastic reduction of amplitude. In particular, there is no indication of a night-time component of daily variation in any year.

The shifting of the hour of maximum to early morning or night hours during 1953-54 has been reported by several other workers. Thus, Possener and Heerden (1956) report that during July, Aug., Sep. of 1953 and June 1954, the hour of maximum of meson intensity measured by inclined (North, South) as well as vertical telescopes at Manchester and London was between midnight and early morning. Steinmaurer and Gheri (1955) report the same behaviour for Ionisation chamber at Hafelekar for 1953-54. Yagi and Ueno (1956) report a similar shift for data from counter telescopes and Ionisation chamber operated at Nagoya and Tokyo, Japan, during 1953-54. Thus all these data show night-time or early morning maxima in 1953-54. However, *all* refer to meson intensity. The question arises whether all these are subject to errors due to temperature correction and if so, to what extent. Since neutron monitor data are not affected by

temperature, it would be interesting to compare these results with neutron monitor data. For the monitor operative at Manchester and later at London, Possener and Heerden (1956) report that the corresponding amplitudes during 1953-54 were not significantly different from zero. From data for Huancayo and Climax neutron monitors, Conforto and Simpson (1957) report that the monthly average vector drifted counter-clockwise during 1954 yielding an *yearly average* amplitude for Huancayo almost zero. For Climax, the average amplitude reduced considerably during 1954 and the hour of maximum shifted to *later* hours in the afternoon. Thus, in general, the neutron monitors showed negligible average amplitudes in 1953-54 and no night-time maxima. This would indicate that the night-time maxima seen in 1953-54 for meson intensities was mainly a temperature effect.

It must be remarked here that such comparisons with neutron monitors are not wholly desirable, because, the purpose of operating meson telescopes is to have an intensity record of mean energy response different from that of a neutron monitor. Thus, one would like to study the *differential* behaviour of neutron and meson intensities rather than equate the two. Therefore, an independent measure of the expected temperature effect would be desirable. If one assumes equality of neutrons and meson effects, some very awkward conclusions follow. Thus Yagi and Ueno (1956) have reported that during 1954, the average amplitude for narrow angle telescopes was 0.3% and the hour of maximum was about 06 hours L.T. If the neutron monitor intensity were any valid comparison, the actual external anisotropy for the same period was zero and hence the temperature effect for narrow angle telescope intensity would work out to 0.3%, in contrast to 0.12% that we have used for correcting the Carnegie Institution data. It is difficult to judge whether such comparisons are invalid or whether temperature effects are really so large. The latter would prove a very disconcerting feature indeed.

It would be interesting to study the behaviour of the amplitude r_2 and hour of maximum ϕ_2 of the second harmonic also. In the past, Sarabhai and Sastry (1960) have reported that the hour of maximum ϕ_2 shifts by as much as 10 hours in 19 years (1939-56) for Huancayo. Here again, the conclusion was based on data which were wrongly pressure-corrected for Huancayo as mentioned earlier. Since pressure curve is predominantly semidiurnal, the error will be largest for the second harmonic of cosmic rays. In the diagram shown by Sarabhai and Sastry in their publication, the value of ϕ_2 changes abruptly from 1946 onwards. This is exactly the period when the wrong pressure correction crept in!

Fig. 9 shows the plots of r_2 and ϕ_2 for Huancayo, Cheltenham and Christchurch, using the properly pressure-corrected data for Huancayo. Following may be noted:

- a) The amplitude r_2 is small throughout, of the order of 0.10% for Huancayo and lesser for Cheltenham and Christchurch. For Huancayo, r_2

increases soon after the solar minima of 1944 and 1954 from values as low as 0.02% to as high as 0.10%. However, r_2 is high at other periods too. Thus, no one-to-one relation with solar cycle is indicated. At Cheltenham and Christchurch, r_2 fluctuates between 0.02% and 0.07% but no correlation between these two stations or with Huancayo or with sunspot cycle is discernable.

- b) The hour of maximum ϕ_2 fluctuates between 0 and 90° (i.e. a fluctuation of about 3 hours) for all stations. However, no intercorrelation between the 3 stations or of any of them with solar cycle is indicated. The large fluctuation of 10 hours (300°) reported by Sarabhai and Sastry is not visible. Also the dotted curves show much reduced fluctuations indicating an appreciable temperature effect.

It seems, therefore, that the second harmonic does not have any definite relation with solar cycle, except perhaps for Huancayo where the amplitude fluctuation shows some relation. This could be an effect confined to equatorial region. It must be noted, however, that the amplitudes are very small ($<0.1\%$) and even small errors in barometric correction could cause large differences. It is also not yet known whether the second harmonic is a meaningful independent quantity. It may as well be an accessory of the first harmonic controlling its sharpness of occurrence.

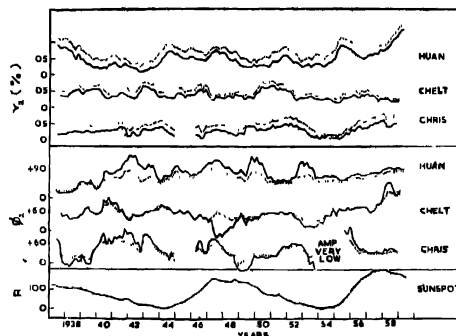


Fig 9 - Long-term changes of the amplitude r_2 and hour of maximum ϕ_2 of the second harmonic before (full lines) and after (dotted lines) temperature correction.

From the average data for 23 years, one can study the sidereal variation; because, the month-to-month change of the solar vector is likely to be very small for averages over such large periods. Fig. 10 shows the monthly average vectors of the first harmonic for Huancayo, Cheltenham and Christchurch after deducting the yearly average vectors from each month. Full curves represent only pressure-corrected data while dotted curves are with additional temperature correction.

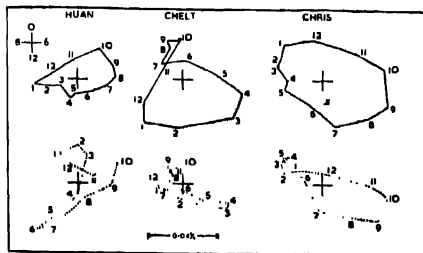


Fig. 10—Harmonic dials for the monthly minus yearly average vectors before (full curves) and after (dotted curves) temperature correction.

Each point is a running average of 3 consecutive months. An anti-clockwise shift of the monthly vector is clear for all stations for pressure-corrected vectors but not for pressure and temperature-corrected vectors. In the absence of a precise knowledge of the magnitude of the temperature effect, valid conclusions regarding sidereal anisotropy are difficult.

CONCLUSION

It is clear from the above discussion that the temperature effect may play a very vital role in the study of the daily variation of ground level meson intensity, specially if the expected amplitudes of external effect are comparable to the expected temperature effect. Unfortunately, there is no way of estimating the latter except by actual measurement of daily variation of upper air temperature. As shown in Table I, the information on this point is very unsatisfactory. Recently some workers of the India Meteorological Department carried out an extensive investigation at four Indian stations (Calcutta, New Delhi, Bombay, Madras, all sea-level stations) for four representative months January, April, July, October. The instruments used were by no means fault-free and, after applying rigorous statistical tests, the following conclusions were arrived at :

- a) Diurnal variation of temperature is generally significant in the lower levels up to 700 mb. only. Under stable conditions such as in January in New Delhi, the daily variation is hardly noticed even at 900 mb. But in July when convection and eddy conduction is very effective, the variation extends even up to 500 mb.
- b) Amplitude of daily variation is about 3°C at 900 mb. reducing to about 1.5°C at 700 mb. Significant values for levels above 700 mb. are also observed but radiation errors are not ruled out.

Such, perhaps, is the situation for all such measurements ! It is interesting to note that whereas a tremendous effort has been put so far and is still continuing to be put, for the continuous recording of cosmic ray meson intensity at ground

levels, not even a fraction of this is devoted by these workers to the measurements of upper air temperature which are so vitally needed for temperature correction. In a recent paper, Teweles and Finger (1960) have done a detailed analysis of comparative the various Radio sonde instruments used in U.S.A.

TABLE VI

Instrument	Solar radiation temperature correction.
(1) Conventional duct-type (double or single) Radiosonde with internally-mounted thermistor.	Radiation error increases rapidly with altitude in middle and upper stratosphere.
(2) Externally mounted (outrigger) white-coated thermistor.	Reflects away 95% of solar radiation. Still radiation error is $\sim 2.0^{\circ}\text{C}$ at 25 mb level with smaller errors below and larger errors above this altitude.
(3) Externally mounted, silvered thermistors employing very small bead and fine tungsten wire (Ney <i>et al.</i> , 1958).	Relatively costly. Presents problems of electrical circuitry. But radiation errors small.

Table VI briefly summarises the types of instruments presently used and their merits and demerits, which are most probably similar for Radio-sonde instruments used all over the world. Workers in several countries have determined radiational temperature corrections for their own instruments. These differ largely from each other, which may be partly due to differences in the instruments at different places and partly because the determined corrections could be erroneous as shown by Teweles and Finger. With uncertainties as large as 2.0°C , the problem of determining the true daily variation of upper air atmospheric temperatures is very formidable indeed. It is unimaginable, however, that it is so difficult as to be beyond the reach of modern technological advance. The instrument of Ney *et al* (1958) is already an indicator of the improvement that can be achieved. The reason for apathy is obviously the lack of realisation of the vital role temperature correction may play in the study of the daily variation of cosmic ray mesons at ground level. It is hoped the present article will serve some useful purpose in bringing out the importance of such a correction and the effort needed to collect the necessary temperature data.

ACKNOWLEDGMENTS

The author is grateful to the various workers who kindly supplied cosmic ray data as well as ground temperature data used in the present analysis. Thanks are due to Prof. V. A. Sarabhai for discussions, to Mr. Blayzar and others for computational assistance and to Atomic Energy Commission of India for financial support.

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